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(54) Method for Determining Directions of Incidence of Wave Energy in a Wide Frequency Range Radiated by a Plurality of Targets

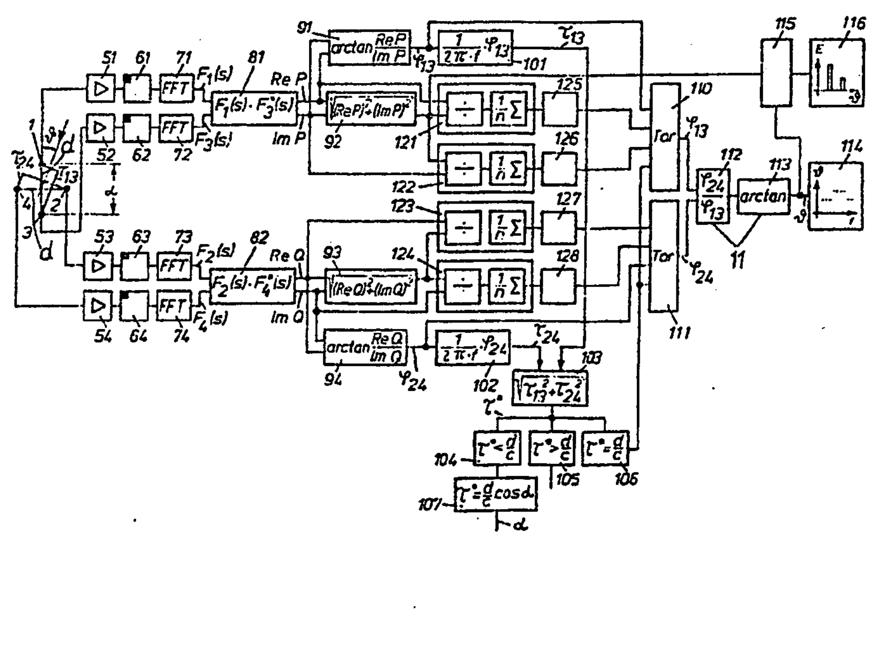
(57) Apparatus for determining the angle of incidenece υ of wave energy comprises a double dipole system of transducers (1, 2, 3, 4), the signals from which are converted to complex frequency spectra ($F_1(s)$, $F_2(s)$, $F_3(s)$ and $F_4(s)$). The spectra corresponding to each dipole and multiplied together in circuits 81, 82, and inverse tangents are formed in phase circuits 91, 94, from the quotients of the real and the imaginary parts of the products, these representing phase differences (ϕ13, ϕ24). Transit times (τ13, τ24) are determined from these phase differences and calculating circuit 103 ascertains the hypotenuse

$$\tau^* = \sqrt{\tau 13^2 + \tau 24^2}.$$

Comparison circuits (104, 105, 106) determine whether τ^* is smaller than, greater than or equal to

$$\frac{d}{c},$$

where d is the distance between the transducers of each pair and c is the speed of propagation of the wave energy.



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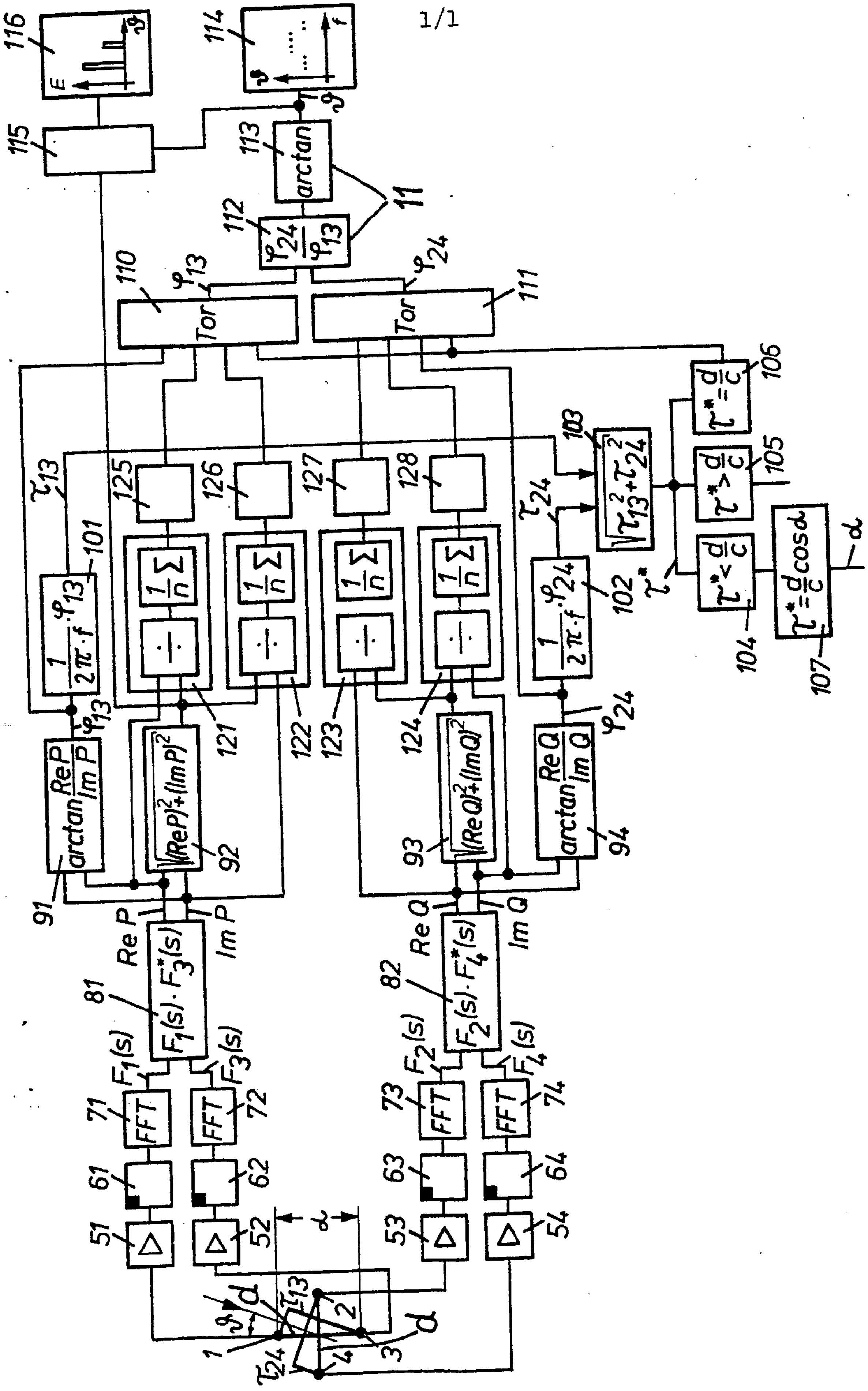

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SPECIFICATION

Method for Determining Directions of Incidence

The invention relates to a method for determining the directions of incidence of wave energy in a wide frequency range, radiated by several targets, using two dipoles, consisting of three converters on the angle points of an isosceles, right-angled triangle or of four converters on the angles of a square.

The direction of incidence of received wave energy which is radiated by a single target is ordinarily determined with two dipoles arranged at right angles to one another, in that the signals received from the two dipoles, taking account of their polarity, are put into the equation. The inverse tangent of the quotient supplies the angle of incidence between the direction of incidence and a connecting line between the converters of one of the two dipoles.

This method however leads to a false result if several targets radiate wave energy simultaneously.

Frequency-selective examinations of the wave energies of several targets show that the targets display different frequency spectra. A separation of the directions of incidence is then possible by means of the frequency, in that only received wave energies of the two dipoles with equal frequency content are set into the equation, since they pertain to the same target. A frequency-dependent division of the wave energy can be realised by a transformation of the received signal into the frequency range. Due to the transformation, size and phase relationships of the received signals are retained.

Such a method is already known for a two-channel visual radio direction-finder with Adcock antenna an Watson-Watt display, from German Publication Specification 22 42 790, in which a frequency spectrum is formed from the signal received from each dipole. The division of the amounts of the frequency spectra for each frequency supplies a quotient which is equal to the tangent of the angle of incidence, and a comparison of the phases indicates the quadrant.

The disadvantage of this method consists especially in that errors can already be caused in the ascertaining of the angle of incidence due to the fact that different sensitivies of the two converters of each dipole falsify the signal obtained by subtraction, on which the frequency-selective further processing is based.

This possible error is avoided in the method known from German Publication Specification 11 98 424, where phase angles are ascertained between the received signals of the individual converters of each dipole and the two phase angles are set into the equation, the inverse tangent of which indicates the angle of incidence. However the disadvantage of this method consists in the frequency-dependence of the phase angle, and is unsuitable for the location of since in the case of wide-band signals no phase angle can be measured.

It is therefore the problem of the present invention to produce a method of the initially stated kind with which, even for a plurality of targets which radiate wave energy in a wide-frequency range, the angles of incidence can be indicated for targets in different directions, while different sensitivities of the converters of the dipoles and also the absolute value of the received signals themselves do not affect the result.

This problem is solved in accordance with the invention in that received signals of the converters are continuously converted, each within an equal predeterminable time interval, into a complex frequency spectrum, in that the phase difference for each frequency is ascertained between the complex frequency spectra pertaining to one dipole and the inverse tangent of the quotient of the phase differences for each frequency indicates an angle of incidence between the direction of incidence and a connecting line between the converters of a dipole as reference dipole.

The complex frequency spectrum of each received signal indicates per frequency by its amount the magnitude of the received wave energy. Its phase angle is composed of an initial phase of the received signal, which is determined by the position of the considered time interval in relation to the zero passages of the received signal, and a term which is proportional to the sine or cosine of the angle of incidence. The initial phase is eliminated by the subtraction of the phase angles of the complex frequency spectra which are allocated to the received signals of the converters of a dipole. The inverse tangent of the quotient of the phase differences thus obtained indicates the angle of incidence per frequency. This method is independent of the sensitivity of the converters, since the amount of the frequency spectra remains out of consideration.

If two dipoles are used the converters of which are arranged on corner points of a square, according to an advantageous further development for freeing the method according to the invention from interference the associated time delay of the incident wave energy is determined between the converters of the dipole from the phase difference, by division with the frequency under consideration and 2π. The time delay per frequency obtained for each dipole are squared, added and the root is extracted. This root is compared with a quotient from the distance between the converters of the dipole and the speed of propagation of the wave energy. By this method it is possible to distinguish whether the evaluation of the phase differences leads to a genuine target indication.

If the root is equal to the quotient of distance of the converters and speed of propagation of the wave energy, the direction of incidence of the wave energy lies in the plane of the dipoles and the wave energy was radiated by a target which is [illegible]

evaluated for the ascertainment of the angle of incidence.

If the root is greater than the quotient, the basis can reliably be adopted that these phase differences do not pertain to received signals from a target but were caused by inteference. Such interference occurs for example in a dipole system, consisting of microphones for the measurement of air-transmitted sound, when apart from target noises, wind noises are received and evaluated which are caused on each microphone due to different air turbulences.

If the root from the sum of the squared time delays is less than the quotient, the associated phase differences are likewise not evaluated, since they do not characterise the direction of incidence in the plane of the dipoles, but are caused by wave energy-radiating sources lying above or below the plane of the dipoles. This selection criterion is advantageous for example when the said dipole system is installed on the roof of a vehicle, the engine or travelling noises of which should not pass into the measurement.

From the cited Publication Specification 11 98 424 it is already known that the sum of the squares of the phase angles of the received voltages of a dipole system is not only frequency-dependent but also proportional to the square of the cosine of an angle of elevation from the plane of the dipoles.

With the method according to the invention the angle of elevation itself can also be determined, which is equal to the inverse cosine of the root of the sum of the squared time delays divided by the quotient. If only targets at elevation angles within predetermined angle limits are to be considered, a separation is possible by a simple comparison with predetermined values for the cosine.

According to an advantageous further development of the method according to the invention the plane in which the direction of incidence is determined is divided over its entire horizon into equal angle sectors, the apex points of which lie at the point of intersection of the connection lines of the dipoles. Wave energy of frequencies the associated incidence angles of which lie within one angle sector are totalled and utilised for the weighting of the targets. This sum is for example obtained by squaring and addition of the amounts of the complex frequency spectrum of one of the received signals, pertaining to the frequencies. Subsequent extraction of the root of the sum results in an effective value of the received signal arriving in this angle sector. In the case of a display of the direction of incidence on an electronic display tube as panoramic display for example the result of this energy consideration can be made clear to the observer by a radial deflection, dependent thereon, of the electron beam. It is also possible by this method to display only directions of incidence of those targets in angle classes corresponding to the angle sectors, over the frequency, the evaluated wave energy of which satisfies a predetermined comparison value.

An apparatus for carrying out the method according to the invention consists of the converters of the two dipoles, amplifiers and series-connected analog-digital converters with stores and calculator stages for a Fast-Fourier transformation. At the output of each calculation stage the real component and the imaginary compoment of the complex frequency spectrum obtained according to the algorithm of the Fast-Fourier transformation are present. In a series-connector calculator unit the phase angle of the complex frequency spectrum is ascertained for each frequency. The phase angles of the frequency spectra of each dipole are deducted from one another in series-connected subtraction stages and divided by one another as phase differences in a quotient former, the phase difference of the reference dipole being present in the denominator. The quotient is fed to a calculator circuit for the formation of the inverse tangent, taking consideration of the signs of the phase differences, at the output of which the incidence angle for each frequency is present in true quadrant, for a display. According to an advantageous further development of the invention the conjugate-complex product is formed from the complex frequency spectra of the received signals pertaining to one dipole, the phase of which product indicates the phase difference, so that an ascertaining of the individual phase angles and the subsequent difference formation do not have to be carried out. By the multiplication moreover a mean value formation is carried out between the two complex frequency spectra.

In a further advantageous development the received signals stored into the memories from a converter of the dipole are read out as they were read in, and the received signal of the other converter are read out of the memory in the converse sequence. The memories are followed by calculator stages for the calculation of the Fast-Fourier transformation, the outputs of which are connected directly with a circuit for the multiplication. The product present at the output has a phase which is equal to the phase difference of the complex frequency spectra of the received signals of a dipole and is utilised directly in the quotient former and in the series-connected calculator circuit for the evaluation of the angle of incidence. This manner of signal processing for each dipole corresponds to a convolution of the received signal to the one converter in the positive time range with the received signal of the other converter in the negative time range. Due to the extraction of the received signal from the memory in the considered time interval in converse sequence to reading in, a time flapping is effected in the negative time range. The result of the multiplication of the complex frequency spectra of the received signals thus removed from the memory is equal to the conjugate complex product of the frequency spectra, if the received

signals are removed from the store in the same way for the Fourier transformation and product formation as they were read in.

In an advantageous further development it is provided that the real and imaginary components of the conjugate complex products are connected to an amount former at the output of which the amount of the product is present. Real and imaginary components are divided in series-connected division stages by the amount of the product—thus standardised—and totalled over a number of time intervals in a totalling circuit and divided by the number. By this signal processing freeing of the received signals from isotropic interference in the transmission medium and electric noises of the utilised component groups for the signal processing is achieved, since a target which is stationary within the number of considered time intervals always possesses the same phase in the conjugate complex product. In interference sources the phase relations vary from time interval to time interval, so that the sum of the standardised real and imaginary components is substantially less than for the targets. In a series-connected comparison stage a control signal is formed if the sum is greater than or equal to a set comparison signal, the comparison signal being selected in dependence upon false alarm probability and detection probability. The comparison stage controls a gate circuit which liberates the phase differences to be evaluated.

When the method according to the invention is used in the technique of water-transmitted sound it is expedient to form the dipole system for example from converters of a cylinder base already present on board a ship. By the distance between the four converters or converter strips on the cylinder base the frequency range to be evaluated is determined, which lies substantially lower than that of the received signals of the directional characteristics of the cylinder base, so that with this arrangement targets especially are detected the radiated wave energy of which lies in the lower frequency range.

One advantage achieved with the invention consists in that the method of phase evaluation for the determination of the angle of incidence in dependence upon the frequency is independent of the absolute value of the received signals and thus also independent of fluctuations of sensitivity of the converters and series-connected component groups for the signal processing. An especial advantage of the method according to the invention consists in that stochastic interference in the transmission medium and electric noises in the component groups are suppressed by consideration of time delay criteria, calculated from phase differences, in the determination of the direction of incidence per frequency. On the other hand due to the same time delay criteria, wave energy of a source not lying in the plane of the dipoles can remain out of consideration in the determination of the direction of incidence.

delay criteria, wave energy arriving through media with different speeds of propagation can be excluded from the determination of the angles of incidence. However it is also possible to distinguish whether the sound received for example from a dipole system consisting of hydrophones under water was radiated from a sound source situated in the water or a sound source situated above water, and was transmitted by a sound wave propagating parallel with the water surface which has penetrated into the water.

The transformation of the received signals selected for the signal evaluation can be realised especially simply with the present day state of the art of calculation, which makes the method of direction determination and the elimination of sources of interference especially simple.

An example of embodiment of the object of the invention is illustrated in the drawing. It shows a block circuit diagram for a signal processing system.

For the ascertainment of the direction of incidence of wave energy which is radiated by one of the targets at an angle of incidence ν, a dipole system is used consisting of four converters 1, 2, 3, 4 which are arranged at corner points of a square having a diagonal d. Between the received signals of the converters 1 and 3, 2 and 4 phase differences ϕ_{13} and ϕ_{24} are determined in dependence upon the frequency. For this purpose the four converters 1, 2, 3, 4 are connected through amplifiers and A-D converters 51, 52, 53, 54 with memories 61 to 64 and calculation stages 71 to 74 for a Fast-Fourier transformation. Received signals on the converters 1 to 4 are amplified, scanned, digitalised and stored. Their time variation within a time interval is converted in each case into a complex-frequency spectrum. As scanned values of the digitally converted received signals of a time interval are stored afresh, the next Fast-Fourier transformation is carried out. The complex-frequency spectra $F_1(s)$, $F_2(s)$, $F_3(s)$ and $F_4(s)$ are present at the outputs of the calculator stages 71 to 74.

The complex frequency spectra $F_1(s)$ and $F_3(s)$ for the received signals of the converters 1 and 3 of the one dipole are multiplied with one another in a circuit 81 in such manner that a conjugate complex product P is produced, in that the frequency spectrum $F_1(s)$ is multiplied with the conjugate complex frequency spectrum $F_3^*(s)$. At the output of the circuit 81 the real component ReP and the imaginary component ImP of the product P are present, from which amount and phase are ascertained per frequency. In a phase circuit 91 following the circuit 81 the inverse tangent is formed from the quotient of real component ReP and imaginary component ImP of the product P, which indicates the phase of the product P as phase difference ϕ_{13}. An amount former 92 is likewise connected with the outputs of the circuit 81 and formes the amount from real component ReP and imaginary component ImP of

the product P by squaring, totalling and root extraction.

The same calculation operations are carried out with the complex frequency spectra $F_2s)$ and $F_4(s)$ of the received signal of the converters 2 and 4 of the second dipole, in that the calculation stages 73 and 74 are connected with a circuit 82 for the formation of the conjugate complex product Q of the frequency spectra $F_2(s)$ and $F_4(s)$, to which circuit an amount former 93 and a phase circuit 94 are connected in series. The phase circuit 94 delivers the phase difference ϕ_{24} per frequency, as phase of the conjugate complex product Q.

From the phase differences ϕ_{13} determined per frequency, associated time delays τ_{13} are obtained in a multiplication stage 101 by multiplications with the reciprocal value of the relevant frequency and with a constant factor

$$\frac{1}{2\pi}.$$

The same calculation is carried out for the phase differences ϕ_{24} in a multiplication stage 102 for ascertaining the time delays τ_{24}.

In a calculation circuit 103 the time delays τ_{13} and τ_{24} ascertained in the multiplication stages 101 and 102 are squared, totalled and the root thereof is extracted. The result

$$\tau^*=\sqrt{\tau_{13}^2+\tau_{24}^2}$$

at the output of the calculator circuit 103 is tested in three comparison circuits 104, 105, 106 as to whether τ^* is smaller or greater than or equal to a quotient of distance d between the converters 1 and 3, 2 and 4 of each dipole and the propagation speed c of the wave energy.

The comparison circuit 104 tests whether

$$\tau^*<\frac{d}{c}.$$

It is connected with a table circuit 107 which compares τ^* with values of a function

$$\frac{d}{c}.\cos\alpha,$$

in order to ascertain therefrom an elevation angle of inclination angle α in relation to the plane of the dipoles, at which the wave energy is received.

If the test results in

$$\tau^*>\frac{d}{c},$$

then a signal appears at the comparison circuit 105 which indicates that the associated phase differences ϕ_{13} and ϕ_{24} are not to be evaluated for the determination of the angle of incidence.

If τ^* is equal to

$$\frac{d}{c},$$

wave energy is received in the plane of the dipoles at incidence angles ν.

In the case of the incidence angle $\nu=0$ the wave energy requires a maximum time delay to pass from converter 1 to converter 3 of the same dipole, which time is equal to the distance d divided by the propagation speed c, namely equal to τ^*. In the case of another incidence angle ν, as illustrated for example in the drawing, between the converters 1 and 3 there lies a time delay of the wave energy τ_{13} and between the converters 2 and 4 a time delay τ_{24}. Over a connection line between the converters and 1 and 3 a right-angled triangle is entered, the longer cathetus of which is equal to τ_{13}. A right-angled triangle over the connection line between the converters 2 and 4 has a shorter cathetus equal to the time delay τ_{24}. It can be shown that these two triangles are equal, so that the two catheti τ_{13} and τ_{24} lie over the hypotenuse

$$\tau^*.\tau^*=\frac{d}{c}$$

is equal according to Pythagoras's theorum to

$$\sqrt{\tau_{13}^2+\tau_{24}^2}.$$

The method according to the invention makes use of this knowledge, in that in the comparison circuit 106 it is tested whether the ascertained time delays τ_{13} and τ_{24} result in a τ^* which is equal to

$$\frac{d}{c}.$$

The comparison circuit 106 actuates gate circuits 110 and 111 to which the phase differences ϕ_{13} and ϕ_{24} are connected. The gate circuits 110 and 111 are followed by an angle-calculator 11 for the quadrant-accurate calculation of the incidence angles ν which in a quotient former 112 forms the quotient per frequency from the phase differences

$$\frac{\phi_{24}}{\phi_{13}}$$

taking consideration of their signs, the phase difference ϕ_{13} standing in the denominator, since the incidence angle ν is measured against the connection line between the converters 1 and 3 as reference dipole. The quotient former 112 is connected with a calculator circuit 113 of the

angle calculator 11 for the formation of the inverse tangent, which circuit is followed by a display 114 for the representation of the incidence angles ν in dependence upon the frequency in Cartesian co-ordinates.

According to an advantageous further development of the invention a further freeing of the display from interference can be achieved in that each amount former 92 and 93 respectively is followed by two division stages with totalling circuit 121, 122 and 123, 124. In the division stage with totalling circuit 121 the real component ReP of the product P is divided by its amount, totalled in each case over a predeterminable number of time intervals and divided by the number. The same calculation operations are carried out in the division stages with totalling circuit 122, 123 and 124 for the imaginary component ImP of the product P and real component ReQ and imaginary component ImQ of the product Q. The division stages with totalling circuit 121 to 124 deliver standardised real components

$$\frac{ReP}{|P|}, \frac{ReQ}{|Q|}$$

and imaginary components

$$\frac{ImP}{|P|}, \frac{ImQ}{|Q|}$$

of the products P and Q. In series-connected comparison stages 125, 126, 127, and 128 it is examined whether the standardised real and imaginary components of the products P and Q are greater than or equal to a comparison signal which is adjustable in dependence upon false alarm probability and detection probability. The outputs of the comparison stages 125 and 126 are connected with the gate circuit 110, the outputs of the comparison stages 127 and 128 with gate circuit 111. Incidence angles ν of wave energy, the stochastic proportions of which are reduced with this signal evaluation by the phase relationships varying from time interval to time interval, are displayed with accurate quadrant on the display 114.

A distinction of the targets according to the power of the received wave energy is possible according to a further advantageous development of the invention in that the plane of the dipoles is divided into angle sectors of equal width and the wave energy received in each angle sector is totalled. In a calculator 115 the incidence angles ν are divided into angle classes which are allocated to the angle sectors. The width of the angle sectors is selected in dependence upon the desired resolution of the direction-finding. The calculator 115 is connected with the amount former 92. The frequencies which pertain to out in the frequency spectrum of the product P and the associated amounts are squared and added up. The sum is displayed as power of the received wave energy over the incidence angles ν divided into angle sectors, as histogram, on a picture screen 116 associated with the calculator 115.

Claims

1. Method for determining the directions of incidence of wave energy in a wide frequency range which is radiated by several targets, using two dipoles consisting of three converters on the corner points of a right-angled isosceles triangle or of four converters on the corner points of a square, characterised in that received signals of the converters are converted continuously each within an equal predeterminable time interval into a complex frequency spectrum, in that the phase difference for each frequency between the complex freqeuency spectra pertaining to a dipole is ascertained and the inverse tangent of the quotient of the phase differences, taking consideration of their signs, for each frequency indicates an angle of incidence between the direction of incidence and a connecting line between the converters of one dipole as reference dipole.

2. Method according to Claim 1, characterised in that for each frequency from the phase difference the time delay of the incident wave energy is determined between the converters of a dipole and in that the two transit times are squared, added and the root is extracted therefrom and this root is compared with a quotient from distance between the converters of the dipole and speed of propagation of the wave energy, and from this a freeing from interference in the determining of the angle of incidence is derived.

3. Method according to Claim 2, characterised in that the phase differences for which the root of the associated squared time delays is equal to or less than the quotient are evaluated for determining the angles of incidence.

4. Method according to Claim 3, characterised in that the phase differences for which the root of the associated squared time delays is equal to the quotient indicate the angles of incidence in the plane of the dipoles.

5. Method according to Claim 3, characterised in that the root which is smaller than the quotient indicates an angle of elevation of the wave energy in relation to the plane of the dipoles, the root divided by the quotient forming the cosine of the angle of elevation.

6. Method according to Claim 1, characterised in that the plane is divided into equal angle sectors the apex points of which lie at the point of intersection of the connecting lines of the dipoles, in that the amounts of the frequency spectrum of one of the received signals are combined for the frequencies ascertained at angles of incidence of

weighting of the power of the incident wave energy.

7. Apparatus for carrying out the method according to Claim 1, using two dipoles of at least three converters with series-connected amplifiers, characterised in that A-D converters, memories and calculator stages for a Fast-Fourier transformation are connected in series with the amplifiers, in that the output of each calculating stage, on which the real and imaginary components of the complex frequency spectrum are present, are connected with a calculator unit for the calculation of the phase angle of the complex frequency spectrum for each frequency, in that the phase angles of the frequency spectra of each dipole are subtracted from one another in a difference stage connected in series with the calculator units and as phase differences are input signals of an angle calculator which consists of a quotient former and a calculator circuit for the formation of the inverse tangent, taking consideration of the signs of the phase differences.

8. Apparatus for carrying out the method according to Claim 1, using two dipoles of at least three converters with series-connected amplifiers, characterised in that for each dipole A-D converters, memories (61, 62, 63, 64) and calculator stages (71, 72, 73, 74) for a Fast-Fourier transformation, on which real and imaginary components of the complex frequency spectrum are present, are connected in series with the amplifiers (51, 52, 53, 54), in that a circuit (81 and 82) for the multiplication of the frequency spectrum of the one received signal with the conjugate complex frequency spectrum of the other received signal of a dipole and an adjoining phase circuit (91 and 94) for the calculation of the phase of this product per frequency are connected in series with the calculator stages of each dipole, this phase indicating the phase difference (ϕ_{13} and ϕ_{24}) of the complex frequency spectra of the received signals of a dipole for each frequency, in that in series with the phase circuits (91 and 94) there is connected an angle calculator which consists of a quotient former (112) for the phase differences (ϕ_{13}, ϕ_{24}) and a calculator circuit (113) for the formation of the inverse tangent, taking consideration of the signs of the phase differences.

9. Apparatus for carrying out the method according to Claim 1, using two dipoles of at least three converters with series-connected amplifiers, characterised in that for each dipole A-D converters and memories are connected in series with the amplifiers, in that the content of the one memory can be read out in the same sequence as in storing and the content of the other memory can be read out in the converse sequence, in that in series with the memories of one dipole there are connected calculator stages for a Fast-Fourier transformation with subsequent circuit for the multiplication of their complex input signals and for the calculation of the phase angle of this product per frequency, the phase angle indicating the phase difference of the complex frequency spectra of the received signals of a dipole for each frequency, in that the phase differences are connected to an angle calculator which consists of a quotient former and a calculator circuit for the formation of the inverse tangent taking account of the signs of the phase differences.

10. Apparatus according to Claim 8 or 9, characterised in that the outputs of the circuit (81 or 82) for real and imaginary components of the product are connected with an amount former (92 or 93) and with a first input each of two division stages with totalling circuit (121, 122 and 123, 124), the second inputs of which are connected together with the output of the amount former (92 and 93), while output signals of the division stage are totalled over a predeterminable number of time intervals in the totalling circuit and in a subsequent comparison stage (125 or 126 or 127 or 128) form a control signal when the sum is greater than or equal to a comparison signal, the comparison signal being adjustable in dependence upon false alarm probability and detection probability, in that the comparison stages (125, 126 and 127, 128) are connected with gate circuits (110 and 111) for the liberation of phase differences (ϕ_{13}, ϕ_{24}) to be evaluated.

11. Apparatus according to Claim 7, 8 or 9 for carrying out the method according to Claim 6, characterised in that for a representation of the angles of incidence (ν) over the frequency in a Cartesian co-ordinate system on an electronic display (114) the X-deflection is controllable by the frequency, the Y-deflection by the angle class and the brightness by the result of the wave energy totalled within the angle class.

12. Apparatus according to Claim 7, 8 or 9 for carrying out the method according to Claim 6, characterised in that for a display of the wave energy over angle classes in Cartesian co-ordinates on a picture screen (116) of an electronic display apparatus, the X-deflection is controllable by the angle classes and the Y-deflection by the result of the wave energy totalled within the angle class.

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